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Abstract: Refractory State Coding (RSC) is a new coding strategy based on a functional model of the stimulated neural population. Our hypothesis is that RSC stimulation would convey the information contained in acoustic signals more effectively, improving sound perception and hearing performance for speech in noise and music. Two main factors that RSC takes into account are channel interaction [1] and refractory properties [2] of the stimulated neural population. They can be characterized by electrophysiological measurements of the evoked compound action potential (ECAP) using "spread of excitation" (SoE) and "recovery function" characterization paradigms respectively [3]. Using this information, for a given stimulus sequence, it is possible to calculate the refractory state of each stimulation site at any given time. In RSC, the stimulus is shaped according to the refractory states of stimulation sites. The spectral representation of the input sound is weighted by the refractory recovery information as well as the electric field distribution function before the next stimulus is selected. The Nucleus 24 and Nucleus Freedom family of cochlear implants incorporate Neural Response Telemetry (NRT) circuitry which is able to conveniently measure the ECAP from the implanted intracochlear electrodes, allowing the model to be custom-fitted to a patient. A software implementation of the standard ACE strategy for the Nucleus Cochlear Implant system is available in the Nucleus Matlab Toolbox. We implemented the RSC strategy in a compatible fashion in Matlab.

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IMPLEMENTATION OF A NEUROPHYSIOLOGICALLY-BASED CODING STRATEGY FOR THE COCHLEAR IMPLANT

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Abstract

Refractory State Coding (RSC) is a new coding strategy based on a functional model of the stimulated neural population. Our hypothesis is that RSC stimulation would convey the information contained in acoustic signals more effectively, improving sound perception and hearing performance for speech in noise and music. Two main factors that RSC takes into account are channel interaction [1] and refractory properties [2] of the stimulated neural population. They can be characterized by electrophysiological measurements of the evoked compound action potential (ECAP) using “spread of excitation” (SoE) and “recovery function” characterization paradigms respectively [3]. Using this information, for a given stimulus sequence, it is possible to calculate the refractory state of each stimulation site at any given time. In RSC, the stimulus is shaped according to the refractory states of stimulation sites. The spectral representation of the input sound is weighted by the refractory recovery information as well as the electric field distribution function before the next stimulus is selected. The Nucleus 24 and Nucleus Freedom family of cochlear implants incorporate Neural Response Telemetry (NRT) circuitry which is able to conveniently measure the ECAP from the implanted intracochlear electrodes, allowing the model to be custom-fitted to a patient. A software implementation of the standard ACE strategy for the Nucleus Cochlear Implant system is available in the Nucleus Matlab Toolbox. We implemented the RSC strategy in a compatible fashion in Matlab.

Introduction

With electric stimulation through a cochlear implant, the excited neural populations within the cochlea react in a much more deterministic manner than under acoustic stimulation. The stimulated neurons have a refractory behavior, which momentarily prevents the neural population from reacting to subsequent pulses that occur in quick succession. Furthermore, the spread of the stimulus electric field is much broader than the field of excitation with acoustic stimulation, the latter making use of the active tuning mechanisms of the basilar membrane.

In standard coding strategies for the Cochlear Implant, neither the refractory properties nor the electric field spread are taken into consideration. The stimuli are generally presented on the selected electrodes as quickly as possible. This likely results in a pattern of activity in the neural population that is excessive, in both the time as well as space dimensions.

The Refractory State Coding (RSC) strategy is intended to produce a less excessive (and hopefully more natural) activity pattern.

Materials and Methods

RSC is an “N-of-M” type of strategy, largely based on the widely used ACE strategy. RSC’s “maxima selection” step is based on a spatio-temporal model, represented by “spread of excitation (SoE)” and “recovery” functions. The SoE functions model the “spread” of the electric field caused by stimulating an electrode, which inadvertently stimulates nearby stimulation sites as well [1] (Figure 1). The recovery functions model the refractory properties of the neural populations at the stimulation sites [2] (Figure 2). These functions are typically patient-specific and can be assigned per stimulation site. Estimates of these functions can be measured with Neural Response Telemetry [3].

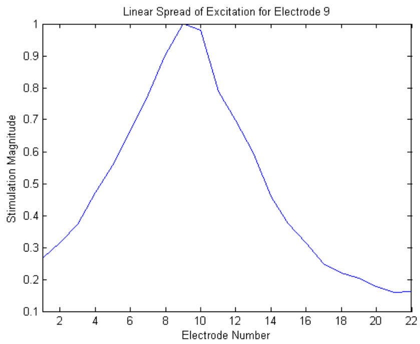

Figure 1*: Spread of Excitation Function*

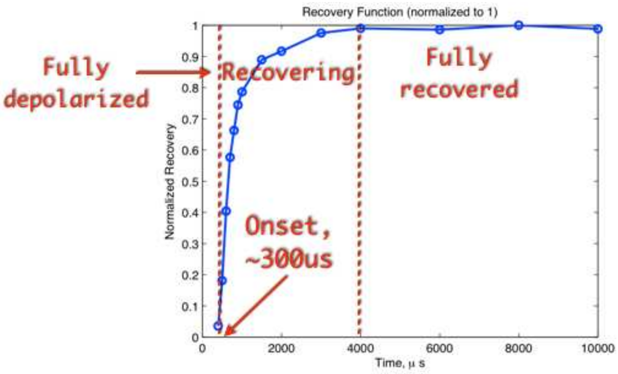

Figure 2: *Recovery Function*

Given an input sound, the RSC follows the same procedure as ACE until and after the maxima selection step (Figure 3). The digital sound is processed by a Fast Fourier Transform, which is subsequently converted to a filter bank output as specified by the ACE algorithm. This produces the so called “stimulation frames” which typically contain 22 amplitude values corresponding to the signal energy in different frequency bands. RSC maxima selection is applied on these frames to obtain the stimulus sequence; loudness and channel mapping steps are then applied, again as specified by ACE, to obtain the output pulse sequence.

The model’s fundamental mechanism is to update the refractory state based on stimuli, weight the stimulation frame with the refractory state, select the next stimulus from the weighted frame, and repeat. The refractory state is updated using SoE and recovery functions. An underlying assumption is that the population percentage of stimulated neurons at a given stimulation site is equal to the power percentage the site is being stimulated at.

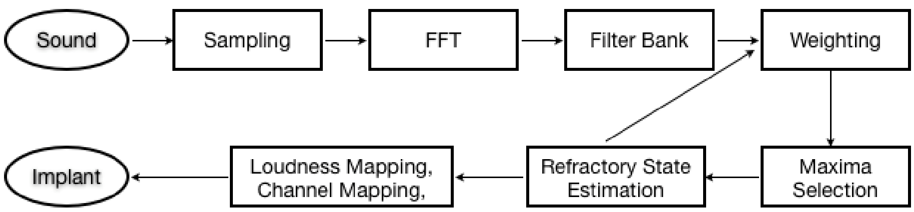

Figure 3*: Block Diagram of RSC Strategy*

In a typical stimulation scenario, initially, the stimulation sites are fully recovered. Thus the first selected stimulus is the highest amplitude of the first frame. The SoE function for that site is scaled with the stimulus magnitude, and is used to weight the refractory state of the stimulus sites in proximity. The stimulated parts of the neural populations are put on recovery paths that follow their site-specific recovery functions.

The new refractory state, estimated using both effects, is used to weight the stimulation frame, from which the new stimulus is chosen. For an intuitive explanation, it can be said that the SoE functions lower the excitability of multiple sites in significant percentages, and recovery functions increase them gradually over time. It's worth noting that when the stimulation frame changes (i.e. after "N" maxima of "M" are chosen), the weighted stimulation frame is obtained naturally by weighting the new frame by the existing refractory state. The refractory state is never discarded.

The RSC strategy was implemented on the software level for evaluation. It was written entirely in Matlab and is compatible with the Nucleus Matlab Toolbox (version 4.31) from Cochlear, also employing parts of it.

Results

We compared the results of ACE and RSC using speech and music signals using 4 and 10 maxima. We observed that the main advantage of RSC over ACE is the ability to maintain spectral information better at lower numbers of maxima (Figure 4). Under typical numbers of maxima, RSC seems to perform very similar to ACE in terms of spectral information, with noticeably lower pulse amplitudes.

Discussion

Better maintaining the spectral information at a lower number of maxima is a direct result of stimulating the neural populations only if they are able to receive the stimuli. We believe this may potentially result in more natural stimulation. The power levels of RSC are overall lower compared to ACE. This provides a minor benefit in power savings, while also potentially making the stimuli softer. This remains to be tested for in subjective tests with CI recipients. The stimulation patterns of RSC are less orderly than ACE stimulation patterns (i.e. seemingly more "random"), which could potentially mean that the RSC stimulation more closely resembles the natural behavior of the healthy cochlea.

Future work includes subjective tests to assess the perceptual effects. We plan to do speech, speech-in-noise and music tests.

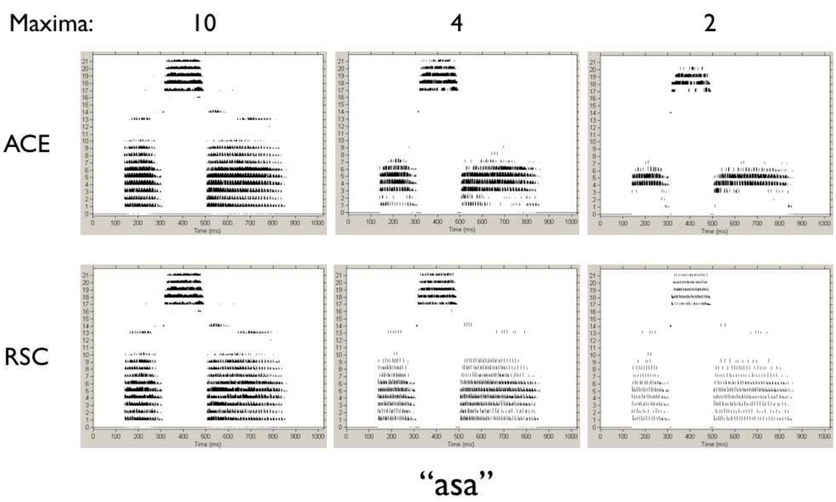

***Figure 4**: Pulse sequences generated for the standard "asa" signal.*

Summary

We implemented a new speech coding strategy based on a spatio-temporal model of neuron population refractory states for the cochlear implant, named Refractory State Coding (RSC). The advantages of RSC over the existing ACE strategy are maintaining the spectral information better at lower number of maxima, and power savings with comparable performance at typical number of maxima.

Literature

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